# TIMESCALE DEPENDENCE IN RIVER CHANNEL MIGRATION MEASUREMENTS

Abstract:

Accurately measuring river meander migration over time is critical for sediment budgets and understanding how rivers respond to changes in hydrology or sediment supply. However, estimates of meander migration rates or streambank contributions to sediment budgets using repeat aerial imagery, maps, or topographic data will be underestimated without proper accounting for channel reversal. Furthermore, comparing channel planform adjustment measured over dissimilar timescales are biased because shortand long-term measurements are disproportionately affected by temporary rate variability, long-term hiatuses, and channel reversals. We evaluate the role of timescale dependence for the Root River, a single threaded meandering sand- and gravel-bedded river in southeastern Minnesota, USA, with 76 years of aerial photographs spanning an era of landscape changes that have drastically altered flows.

Empirical data and results from a statistical river migration model both confirm a temporal measurement-scale dependence, illustrated by systematic underestimations (2–15% at 50 years) and convergence of migration rates measured over sufficiently long timescales (> 40 years). Frequency of channel reversals exerts primary control on measurement bias for longer time intervals by erasing the record of observable migration. We conclude that using long-term measurements of channel migration for sediment remobilization projections, streambank contributions to sediment budgets, sediment flux estimates, and perceptions of fluvial change will necessarily underestimate such calculations.

## Introduction

### Fundamental concepts and motivations

Measuring river meander migration rates from historical aerial images is useful for developing a predictive understanding of channel and floodplain evolution (Lauer & Parker, 2008; Crosato, 2009; Braudrick et al., 2009; Parker et al., 2011), bedrock incision and strath terrace formation (C. R. Constantine et al., 2009; N. J. Finnegan & Dietrich, 2011; Motta et al., 2012; Gran et al., 2013), as well as providing constraints for sediment budgets (S. W. Trimble, 1983; Reid & Dunne, 2005; Belmont et al., 2011) and bank erosion models (Larsen et al., 2006; Motta et al., 2012). Historical meander migration rates are also used to study if, and to what extent, channel migration rates have changed over time. Rivers respond to climate and land use changes via nonlinear adjustments to channel, width, depth, planform pattern, vertical incision or aggradation, and lateral migration (Nanson & Hickin, 1983; Simon, 1989; D. Gaeuman, Schmidt, et al., 2005; Swanson et al., 2011; Toone et al., 2014; Larsen et al., 2006; Call et al., 2017). Ultimately, channel adjustments shape fluvial and riparian habitats and may pose risks for nearby human infrastructure (Wente, 2000; Allan, 2004). Accurate measurements of migration rates are essential for advancing our understanding of river adjustment across a range of spatial and temporal scales.

Increased availability of historical and contemporary landscape-scale data (e.g., aerial photographs and high-resolution topography, HRT) have improved the accuracy and precision of channel migration measurements over short (<1 year) and long (> 50 years) timescales, and thus interpretations of fluvial patterns, processes and trends (Lindsay & Ashmore, 2002; Ghoshal et al., 2010; Donovan et al., 2015; Passalacqua et al., 2015). However, timescale dependence of process rate measurements, often referred to as 'Sadler effects' (Peter M. Sadler, 1981), may bias interpretations and hinder attempts to untangle the complexity of river responses to changing climate and land use conditions (Gurnell et al., 1994; Larsen et al., 2006; Micheli & Larsen, 2011; Schook et al., 2017). We use ‘timescale dependence’, rather than ‘Sadler effects’, because channel migration and accompanying measurements occur over much shorter timescales than geologic phenomena, and are affected by factors other than those discussed by Sadler (1981).

Timescale dependence has been demonstrated for a multitude of unsteady processes, including sediment accumulation, aggradation, progradation, and degradation (Peter M. Sadler, 1981; Gardner et al., 1987; Lindsay & Ashmore, 2002; Kessler et al., 2013; P. M. Sadler & Jerolmack, 2015), river incision (Noah J. Finnegan et al., 2014; Gallen et al., 2015), mountain erosion (Kirchner et al., 2001), cliff erosion (Cambers, 1976), and slope adjustments (Penning-Rowsell & Townshend, 1978). Spatially averaged (mean) erosion rates such as sediment yield appear to be independent of measurement timescale because they integrate across local extents of erosion and deposition (P. M. Sadler & Jerolmack, 2015; Ganti et al., 2016). While research has compared short-term erosion pin measurements with long-term measurements derived from tree rings or aerial image comparisons (J. M. Hooke, 1980; Nanson & Hickin, 1983; Thorne, 1981), the potential for timescale to disproportionately affect short- and long-term measurements of river migration has not been addressed.

Process hiatuses (e.g., rapid change followed by periods of dormancy) and reversals (e.g., incision vs. aggradation) appear to be largely responsible for timescale dependence across a variety of unsteady processes (Peter M. Sadler, 1981; Gardner et al., 1987; Noah J. Finnegan et al., 2014; P. M. Sadler & Jerolmack, 2015). In the case of channel migration, both factors likely influence measurement-scale dependence, with reversals defined as episodes of left vs. right migration, rather than incision vs. aggradation. Intuitively, channel reversals necessarily lead to underestimating the total/gross migration because observed/net migration approaches; with apparent rates approaching zero as the channel migrates back to the position in the initial photo.

Highly confined channels with high sediment load may experience higher degrees of channel reversals as they 'bounce' off nearby valley walls more often than an unconfined channel with a wide meander belt.

In order to understand timescale dependency in channel migration measurements, we analyze empirical and synthetic datasets to address the following questions: Does timescale dependence exist for river migration measurements? If so, how does it affect our ability to accurately measure and compare changes in migration rates over time? What mechanisms cause measurement timescale dependence, and to what degree? Can timescale dependence and actual changes in channel migration be disentangled in order to determine if/when/where real changes in migration rates have occurred? We explore these questions using a statistical model as well as empirical data from the Root River, in southeastern Minnesota, USA. While we focus on channel migration measured from aerial images, our insights are applicable to process rates measured using other platforms, such as repeat topographic surveys, or HRT.

## Study area and Data

We evaluate timescale dependence empirically using 12 sets of aerial photographs spanning 120 km of the Root River, Minnesota, a single-threaded, meandering sand- and gravel-bedded river that drains into the Mississippi River (Figure 2-1). Images span 76 years (1937, 1947, 1953, 1976, 1981, 1991, 2003, 2006, 2008, 2010, 2011, and 2013). We selected the Root River because it exhibits three distinct geomorphic settings (Table 2-1) that provide an opportunity to explore differences in measurement-scale dependencies and channel migration patterns for each setting. These distinct geomorphic environments are relics of the Late Pleistocene and Holocene history of glaciation and base level changes and are characterized by different degrees of valley confinement, slope, and sinuosity (Souffront, 2014; Belmont, Dogwiler, & Kumarasamy, 2016). While it is not the goal of this study to examine how changes in land use and flow affect migration rates, the geomorphic setting provides useful context to interpret our results.

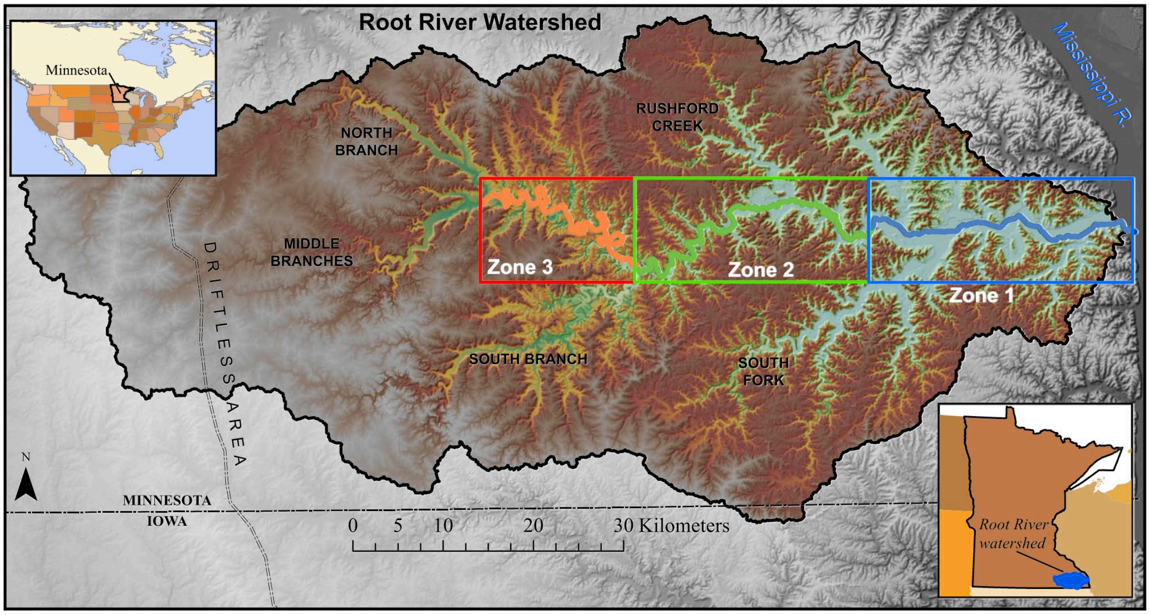


Figure 2-1. Overview map of the Root River watershed and three distinct geomorphic zones as defined by Souffront (2014). Each zone has a unique slope and degree of valley confinement. The extent of delineated river spans 120-km of river length, with Zones 3, 2, and 1 having lengths of 42, 38, and 32 km, respectively.

Table 2-1. Root River zones and morphological characteristics

| Characteristic | Zone 3 | Zone 2 | Zone 1 |
|---|---|---|---|
| Length (km) | 46 | 47 | 34 |
| Drainage area[a] ($km^2$) | 160 | 301 | 431 |
| Median channel width (m) | 42 | 50 | 65 |
| Median valley width (m) | 261 | 683 | 1314 |
| Sinuosity | 1.10 | 1.23 | 1.04 |
| Slope (m/m) | 0.0010 | 0.0006 | 0.0005 |

[a]Farthest downstream point.

The 120 km study reach is partially within the so-called ‘Driftless Area’ of the upper Midwestern United States, which has been unglaciated for the past 500 kyr (Syverson & Colgan, 2004), but received glacial melt water and outwash from the glaciated western portion of the watershed following the Last Glacial Maximum (LGM). Deep valleys within the Driftless Area resulted from incision of the Mississippi River prior to the LGM (Baker, Knox, Lively, & Olsen, 1998; Knox, 2006). These alluvial valleys are surrounded by rolling uplands that are largely forested in steeper areas (> 10°) of the watershed, with corn and soybean farming on gently sloping areas. Row crops occupy approximately 75% of the watershed and are dominant throughout the previously glaciated western portion. Shallow karst underlies the majority of the Root River watershed, with typically less than 15 m of alluvial deposits overtop carbonate bedrock. Mainstem valleys and larger tributaries run across mantled karst with alluvial deposits exceeding 30 m.

While improved agricultural management in the 1940s reduced upland erosion from agricultural fields, the legacy of historical agricultural erosion still represents a significant sediment source in the form of large alluvial terrace and floodplain deposits along the modern Root River (Stout & Belmont, 2013; Stout, Belmont, Schottler, & Willenbring, 2014; Belmont, Dogwiler, et al., 2016). Historical milldams and small hydroelectric power dams exist along some tributaries, as well as levees along the mainstem outlet along downstream reaches of Zone 3.

The Root River hydrologic regime has experienced significant increases in both low and high flows (80 and 60% increases, respectively) over the past 40 years resulting from enhanced artificial drainage of agricultural lands and increasing precipitation (Lenhart, Peterson, & Nieber, 2011; Stout et al., 2014; S. A. Kelly, Takbiri, Belmont, & Foufoula-Georgiou, 2017). Changes in sediment loading over time have not been examined, although the land use history bears many similarities to the well-studied Coon Creek, directly across the Mississippi River (S. W. Trimble, 1999; Stanley W. Trimble, 2009). The Root River watershed exhibits some of the steepest relationships between discharge (Q) and total suspended solids (TSS) throughout Minnesota (Vaughan, Belmont, Hawkins, & Wilcock, 2017), indicating the presence of considerable near-channel sediment sources that are highly vulnerable to erosion, especially under high flow conditions (Stout et al., 2014; Belmont, Dogwiler, et al., 2016). Combining three distinct geomorphic settings with the spatially (120 km) and temporally (76 years) robust set of historical air photos provides an exemplary opportunity to explore timescale dependence of migration measurements along an alluvial river experiencing increased flow.

## Methods

### Measuring and evaluating temporal change

Approximately 2,880 km of streambanks were digitized from 12 sets of scanned georeferenced images (Souffront, 2014; M.S. Thesis) and used to interpolate channel centerlines for each year (1937, 1947, 1953, 1976, 1981, 1991, 2003, 2006, 2008, 2010, 2011, 2013). For every combination of two images (n = 66), curvature-driven cut-bank migration magnitude was measured at 10-meter increments along the channel using the Planform Statistics Toolbox (Lauer, 2007; Lauer & Parker, 2008). We do not distinguish between cut-bank migration, down-valley translation, and/or bend expansion/contraction in our measurements, because results exhibit < 1% difference based on preliminary comparisons. Total migration was measured as distance between a node on the initial and terminal channel centerlines (Fig. 2-2). We manually identified and filtered out meander bend cutoffs for relevant measurements (i.e., affected image pairs) before performing subsequent analyses. Although the length of river filtered out as cutoffs increased with the measurement interval, the proportion of length filtered out was trivial compared to the entire 120 km study reach.

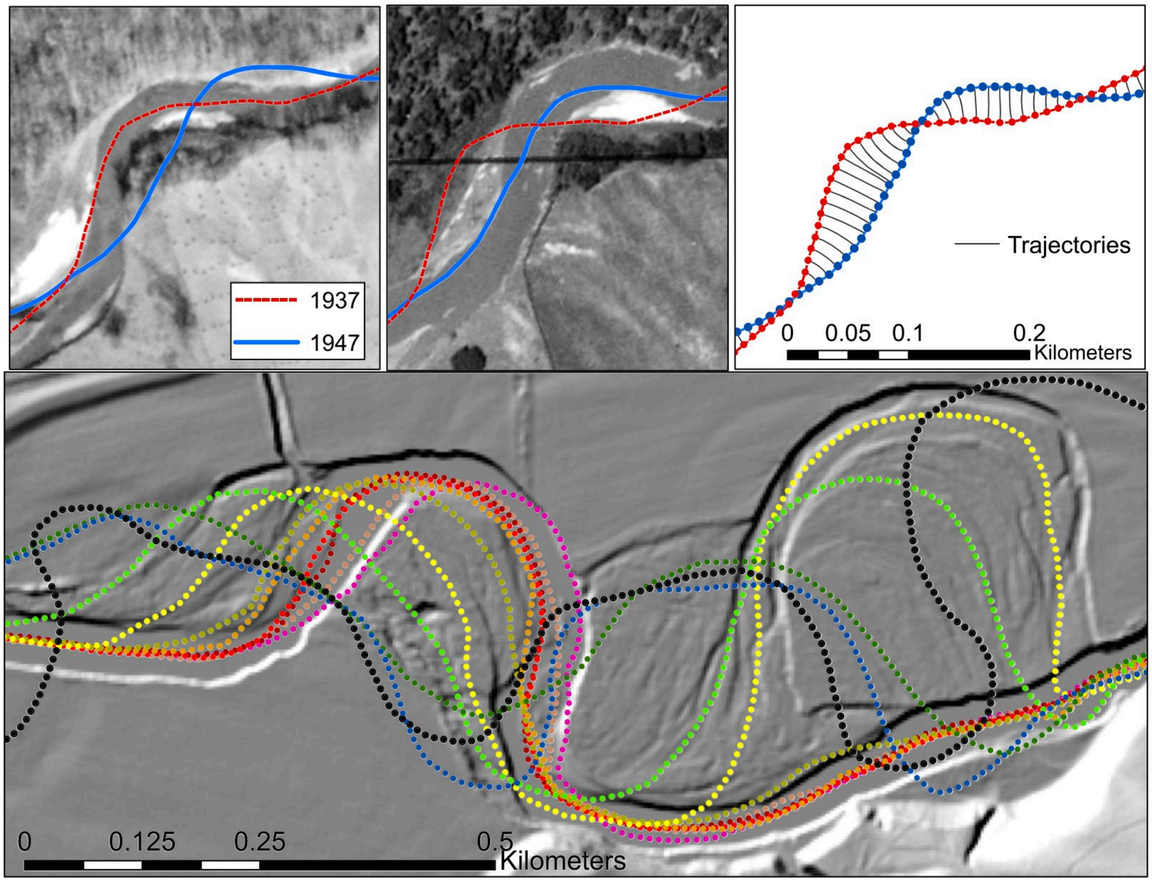


Figure 2-2. Images depicting a general idea of migration measurements as described in the text. Top left and center images show the 1937 and 1947 imagery, respectively, overlain by the channel centerlines. The top right image depicts 10-m increments at which the migration distance is calculated using the Planform Statistics Toolbox (Lauer, 2007). Bottom image illustrates 12 channel centerlines derived from the images spanning 1937–2013, with points at 10-m increments.

Because different geomorphic conditions can lead to unique channel responses (Montgomery, 1999), we binned migration rates into three distinct geomorphic zones previously classified by (Souffront, 2014) based primarily on slope and valley confinement (Fig. 2-1, Table 2-1). Lognormal distributions dominated our migration measurements, so we tested for significant increases in the medians, extremes, and distributions of each image pair using nonparametric statistics (Mann-Whitney Wilcoxon and Kolmogorov-Smirnov tests). We tested the alternative hypothesis that migration rates have increased with flow using one-tailed tests with alpha-values of 0.05 to ensure 95% confidence of avoiding a Type I error. Because 95%

confidence levels can be excessive in water resource and environmental risk applications and are not always germane (Johnson, 1999; Belmont, Stevens, Czuba, Kumarasamy, & Kelly, 2016), we also evaluated significance at alpha values of 0.1 and 0.2 (Appendix C, Table A1a & A1b).

Measurement intervals differed for image pairs between 2003-2013 ($\Delta t \sim$ 1-3 years) and those prior to 1991 ($\Delta t \sim$ 6-23 years), possibly confounding results. Thus, we also compared pre-1991 rates with ensemble rates measured from 2003-2013 ($\Delta t = 10$, $n = 18$), providing the second line of evidence for whether migration rates have changed. In the case that fewer years exhibited differences after comparing migration measured over 2003-2013, timescale bias may have confounded or influenced inferences of channel response to hydrologic changes.

Measurement length-scale dependence

We computed and plotted correlograms of Geary's C (Geary, 1954) to quantify the lengths over which spatial measurement autocorrelation exists in our river migration data, which results from autocorrelation inherent in river migration as well as local-scale systematic delineation biases. Spatial autocorrelation generally persisted until 50-200 m length-scales, beyond which it was extremely weak to none (C-values > 0.8). Thus, we averaged migration rates over 400-meter increments to ensure autocorrelation did not compromise the validity of the statistical tests implemented. Nevertheless, we used a range of length scales above and below 400-meters to confirm that length scale had negligible effects on timescale dependency results. The Geary's C results informed our decision to model migration over 400-m increments. Specifically, knowing that migration rates are not autocorrelated at length scales longer than 400 m allows us to randomly sample the distributions of migration rates, which were derived from empirical data, without concern for spatial autocorrelation.

Quantifying uncertainty from georeferencing and digitization error

We quantified uncertainty as the sum of squares from spatially variable georeferencing uncertainty and uniform user delineation/digitization to estimate the minimum level of detection (LoD). Georeferencing uncertainty was calculated for at least 185 georeferenced control points (GCPs) for each year and interpolated to obtain uncertainty for each raster cell (Lea & Legleiter, 2016). Digitization uncertainty was estimated by comparing centerlines derived from 4-repeat streambank digitizations of the same 11-km reach. We assigned values of zero to migration measurements below the minimum LoD (see flat portions, Fig. 2-4a – k).

Distinguishing timescale dependence

Following established methods for assessing timescale dependence (Gardner et al., 1987; P. M. Sadler & Jerolmack, 2015; Ganti et al., 2016), the mean channel migration (Δx, mean of all 400-m reaches) was plotted against the respective time interval (Δt, 1-76 years, *n* = 66) in log-log space (Fig. 2-5). Trends of log(Δx) over log(Δt) for each zone were compared to a 1:1 line visually and using an their 98% (3σ) confidence intervals to evaluate whether channel migration exhibited systematic bias with longer averaging time scales. Research assessing timescale dependence for timescales spanning multiple orders of magnitude (Gardner et al., 1987a; Sadler and Jerolmack, 2015; Ganti et al., 2016) compare mean adjustment (Δx) against the respective time interval (Δt) in log-log space with a 1:1 line. Significant deviations from the 1:1 line indicate a measurement-scale dependence, but can also reflect systematic shifts in rates over time. Because our aerial images span less than a century (76 years), and to avoid the possibility of confounding timescale dependence with systematic changes, we evaluate the process rate (Δx/Δt) over the time interval (Δt) on linear axes. We test whether systematic rate changes or sample bias are the source of observed timescale dependence by comparing historical and contemporary migration rates for a subset seven specific reaches (3-29 km, Appendix C, Fig. A3) having similar short measurement intervals ($\Delta t \leq 6$ years). This comparison used commensurate timescales and filled in our sample gap (i.e., historical data with short $\Delta t$), thereby providing an independent and unbiased third line of evidence indicating whether: 1) migration rates changed systematically over the period of study, and 2) observed timescale dependence actually reflected a dearth of short-$\Delta t$ measurements for historical data, rather than an actual change in migration rates. We further examined how sampling bias may affect timescale dependence using a statistical model (described later).

The overwhelming majority of past literature demonstrate that process reversals and hiatuses are mechanisms for causing timescale dependence and/or bias. We expected the Root River to have relatively low reversal rates due to its wide valley and meander belt. Nonetheless, we manually measured the length of channel that had reversed within the period of study to inform and support our statistical model that explores mechanisms of measurement bias. The criteria required that reversals be maintained for multiple years/images, ensuring exclusion of 'fake' reversals in the form of offset for single year due to georeferencing of digitization error. For this reason and due to the data structure, measuring reversal length by hand was necessary and allowed us to use our expert judgement that an automated classification would lack. In our evaluations, we omitted data after 1991 because the time intervals were too short to discern reversals from noise.

## Discerning processes responsible for timescale dependence in channel migration

To explore the effects of hiatuses (e.g., rapid change followed by periods of dormancy) and reversals (migration opposite in direction to previous records) we developed a statistical model that simulates river migration and reversals, without involving unnecessary details regarding their underlying mechanisms. We developed the model to explore whether, and to what degree, migration hiatuses, channel reversals, and temporal shifts in migration rates affect migration measurement bias. To do so, we synthesized a 'complete' dataset representing annual migration measurements. Specifically, we generated 100-year synthetic annual migration rates for 100 reaches, each 400-m in length. Rates were randomly selected from the range of lognormal distributions found in empirical data from the Root River with $\Delta t \leq 3$ years ($n_{years} = 7$, $n_{obs} = 2247$), including 0-values, which comprise 50 to 75% of the values. The model script randomly chose mean values from the entire range (0.31-1.42 m/yr) of empirical mean migration rates for years with $\Delta t \leq 3$ years and generated variance ($\sigma$) using an empirical linear relationship (Eq. 2; Appendix B, Fig. A2). For the initial year of the model, all migration rate values are positive, representing the rates of migration in either direction (i.e., right or left, the initial direction of movement of any given reach is irrelevant for our purposes). The model computed standard deviation based on the randomly selected average migration rate value using Eq. 2, because empirical data indicate that standard deviation varies directly, and significantly, as a function of the mean migration rate (SI, Fig. 2).

$$\sigma = 0.36(\mu\left(\frac{\Delta x}{\Delta t}\right)) + 1.25 \tag{2}$$

Due to the high likelihood that the occurrence of channel reversals leads to underestimating measured migration rates, we evaluated the effect of reversal frequency using four model scenarios. In the absence of literature quantifying the temporal frequency or probability of channel reversals, we evaluated a range of plausible reversal frequencies (0%, 1%, 2%, 5%, and 10%), supported by observations for the Root River. The frequency of reversals explored in our model reflects a reasonable range of what we expect to occur in natural systems; reversal frequency varied from 1-6% across the definitive geomorphic zones of the Root River. Highest reversal frequency lie in the confined upper reaches and decreased downstream, which supports intuition that reversal frequency is inversely related to valley width and our decision to model reversal frequencies from 1 to 10%. Reversal frequency was implemented by probabilistically reversing simulated migration (i.e., multiplying migration rates for individual reaches by -1) until the end of the 100-year model run, or until chance (1%, 2%, 5%, or 10%) reversed the 400-m segment back to its original direction (i.e., a positive value). The model tracked cumulative migration distance for each 400-m reach, and thus, negative values (i.e., reversals) reduced the modeled cumulative migration distance and rate. Similar to our analysis of empirical data, we calculated the mean for all 400-m segments to represent the ensemble mean annual river migration. We plotted all possible Δt combinations of average (mean) migration rate to evaluate how increasing reversal frequency affected timescale dependence.

In addition to hiatuses and reversals, systematic changes in migration rates may also cause trends in timescale dependence to diverge from a 1:1 relation, especially if recent photos dominate shorter timescales (Δt) and longer timescales are dominated by older photos acquired at lower frequencies. We conducted an additional set of model runs to explore the effect of older photo sets typically dominating longer timescales, coupled with the impacts of systematic changes in migration rates. We generated scenarios wherein contemporary migration rates (i.e., years 51-100) were increased and decreased by factors of 1.25, 2, 5, and 10 relative to historical rates (i.e., years 1-50, Fig. 2-3). These scenarios also had a 10% chance for channel reversals. Outputs from these eight scenarios of change allowed us to evaluate whether temporal changes in migration rates cause a false-positive timescale dependence, indicated by a shift/translation to the trends in Fig. 7a. We implemented a second test to verify or refute these results in which we compared the entire population of simulated migration measurements (n= 4950) to a sample of simulated measurements (n= 120) that reflected typical datasets having dominantly short Δt measurements from contemporary photos and long $\Delta t$ measurements from historical photos (SI, Appendix D, Fig. A4).

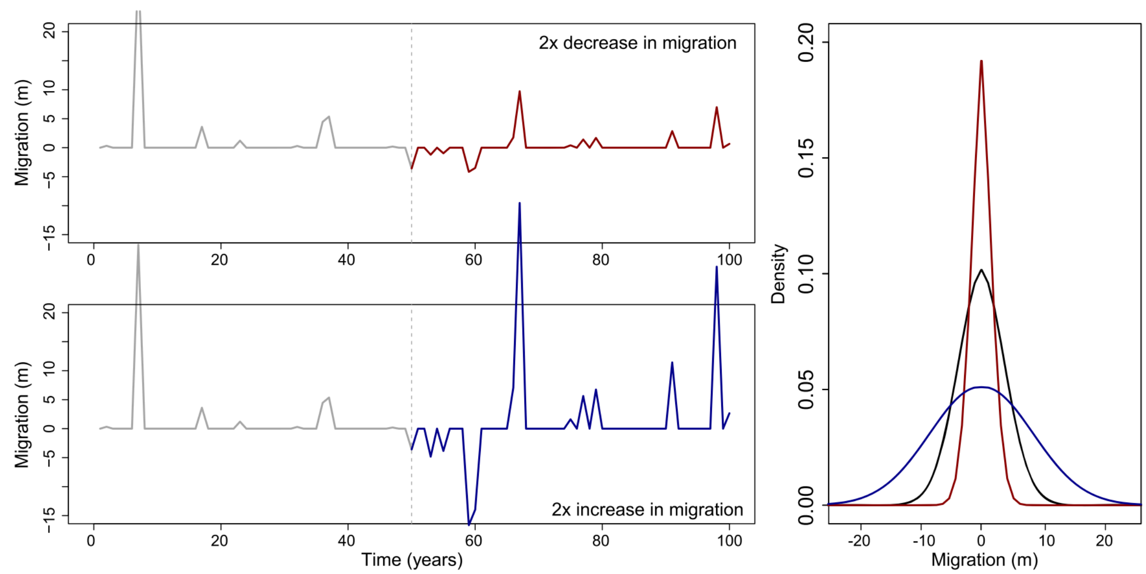


Figure 2-3. Numerical simulations of annual migration for 100-years of a single 400-m reach. (Top) Dark shaded ‘modern’ values are twice as high as historical values from years 1–50. (Bottom) Light shaded values are 50% less than the darker, contemporary rates from years 51–100.

## Results and Discussion

### Does timescale dependence exist for river migration measurements?

The entire 120 km dataset of migration rates for adjacent time intervals are illustrated in Figure 2-4a-k, where channel cutoffs and measurements below the LoD are plotted as zeros. Measurements of mean channel migration exhibit a visual timescale dependence for each zone of the Root River (Fig. 2-5a). Loss of a record due to channel reversals would be similar to vertical reversals (e.g., sediment aggradation vs. erosion) that cause bias in other measurements by erasing historical records (Sadler, 1981; Gardner et al., 1987b; Sadler and Jerolmack, 2015; Ganti et al., 2016). Reversals in migration direction (Fig. 2-6) occurred over 23 km (17%) of the Root River, and thus, were a possible mechanism underlying the timescale dependence. The percent and length of reversals declined from upstream to downstream reaches (66%, 32%, and

0.5% for Zones 3, 2, and 1, respectively), which is consistent with expectations because upstream reaches are exhibit higher migration rates and are confined within narrower valleys (Table 2-1). Post-hoc correlations and regressions showed a significant ($p < 0.001$, $r2 = 0.98$) indirect relationship between the frequency (length and percent) of reversals and valley width (Appendix A, Fig. A1). On the other hand, long-term rates may simply appear to have systematically low rates because our longer $\Delta t$ values are dominated by historical air photos during periods when migration rates may simply have been slower. However, no systematic shifts were evident when comparing a subset of historical reaches ($n = 7$, 3-29 km, Appendix C, Fig. A3) with short measurement intervals ($\Delta t \leq 6$ years) to contemporary measurements with similar $\Delta t$. We further explore this possibility using a statistical model of migration.

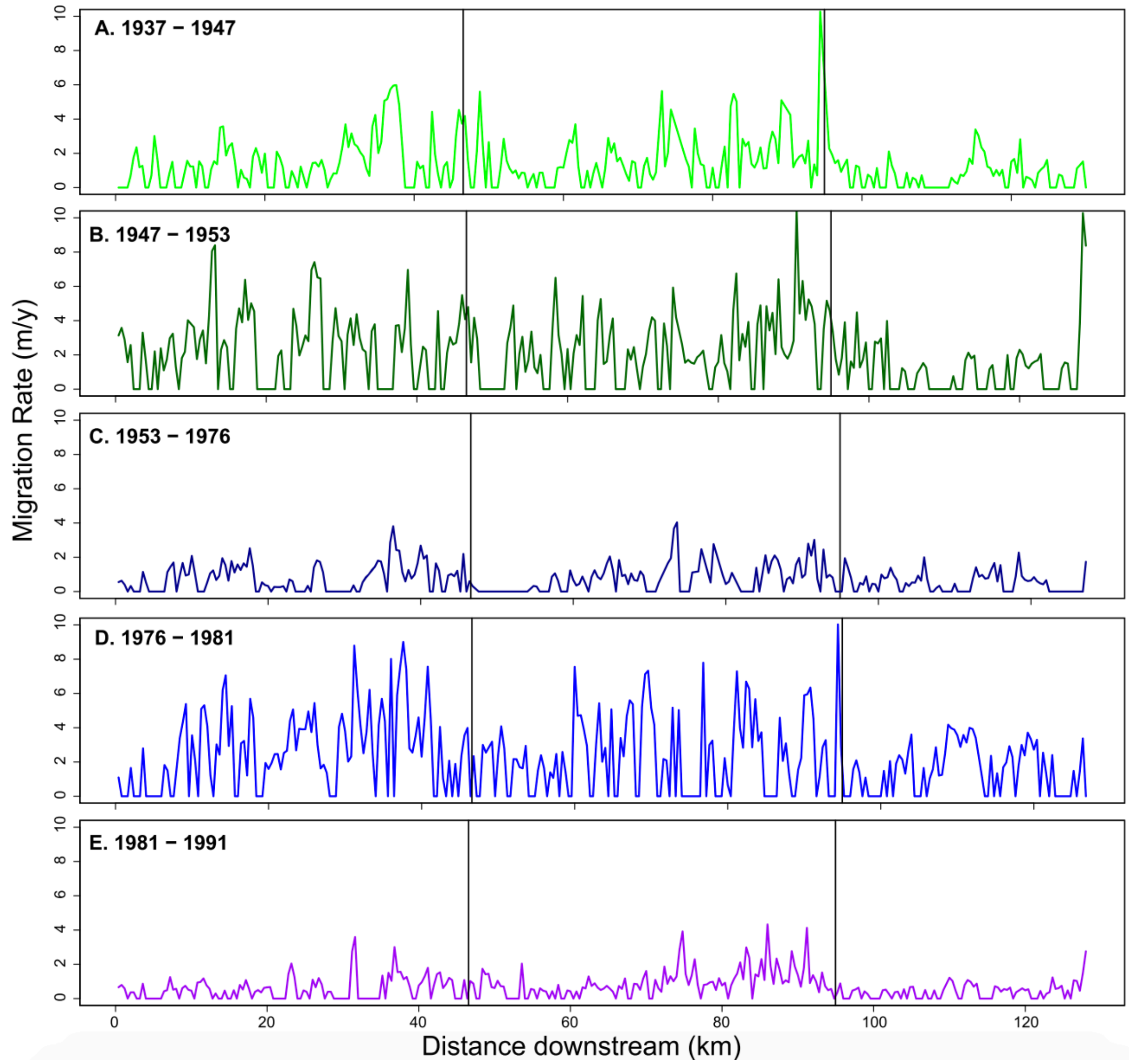


Figure 2-4. (A–E) Longitudinal profiles of migration rates for five measurements made between 1937 and 1991.

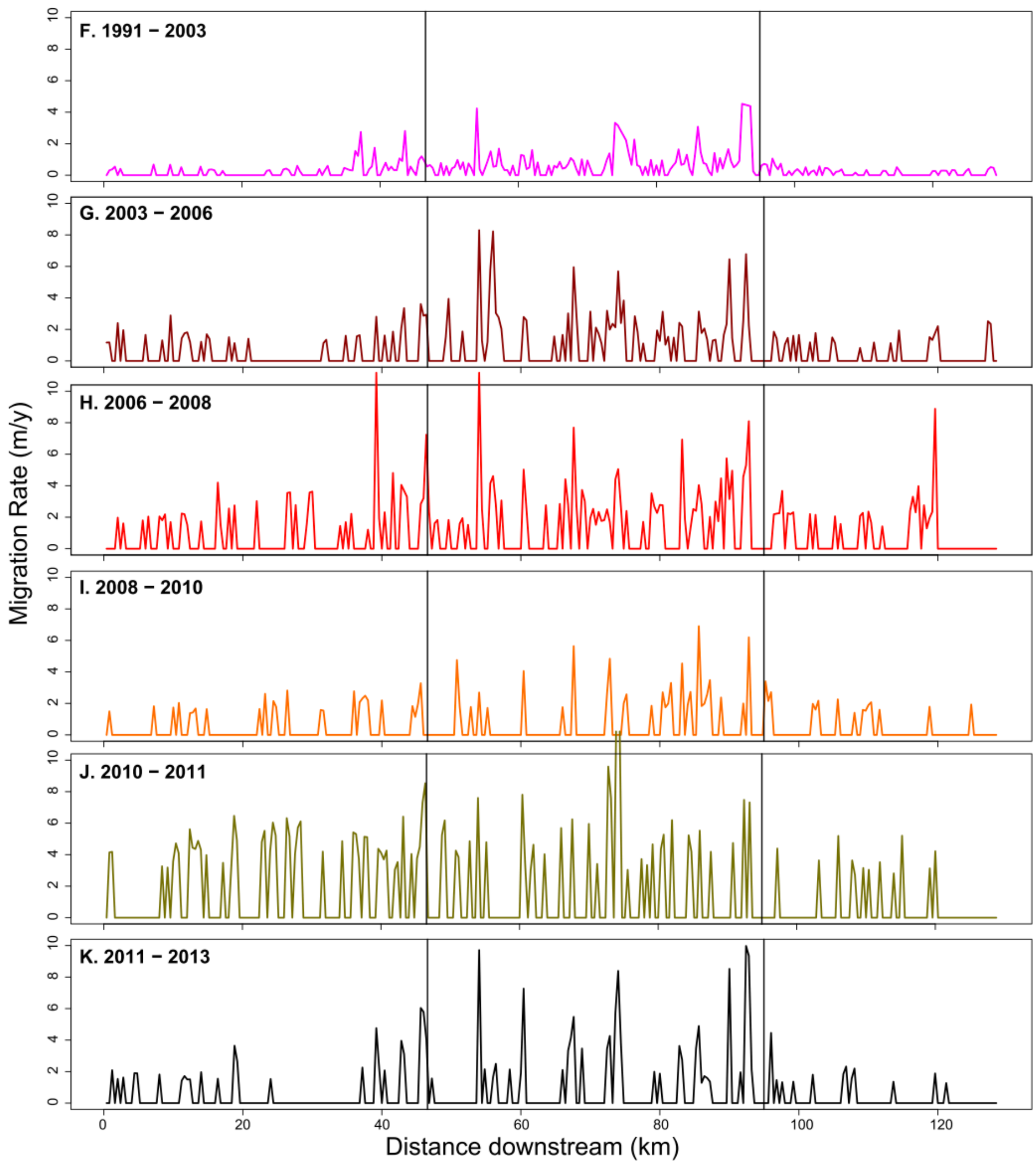


Figure 2-4. (F–K) Longitudinal profiles of migration rates for six measurements made between 1991 and 2013. Vertical black bars indicate demarcations of Zones 3, 2, and 1, from left to right.

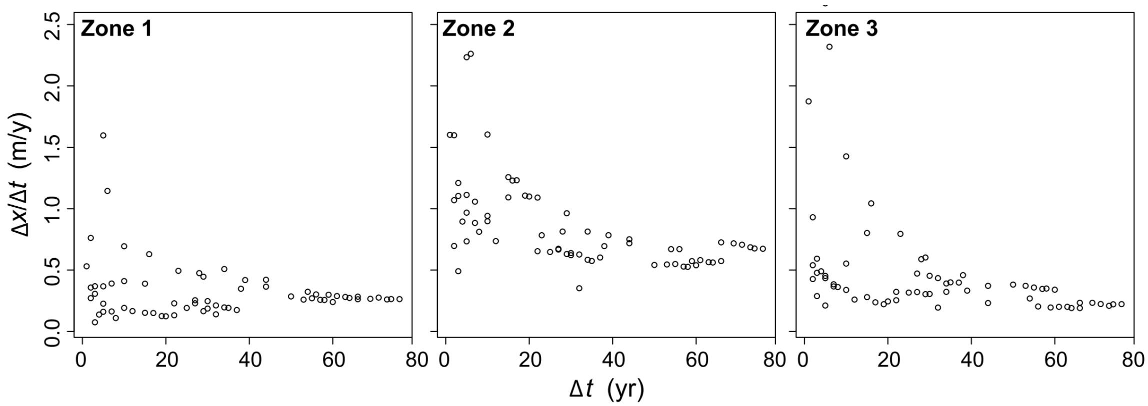


Figure 2-5. Each black circle represent mean migration rates for a zone (34–48 km) of each aerial photo pair (e.g., 1937 – 1947, Figure 2). Variability in migration dominates the signal in short-term rates, whereas rates to converge over broader time intervals as broad measurement intervals dampen short-term variability. Measured rates systematically decrease and converge as Δt increases, indicating that migration measurements are dominated by channel dormancy and reversals at longer temporal scales.

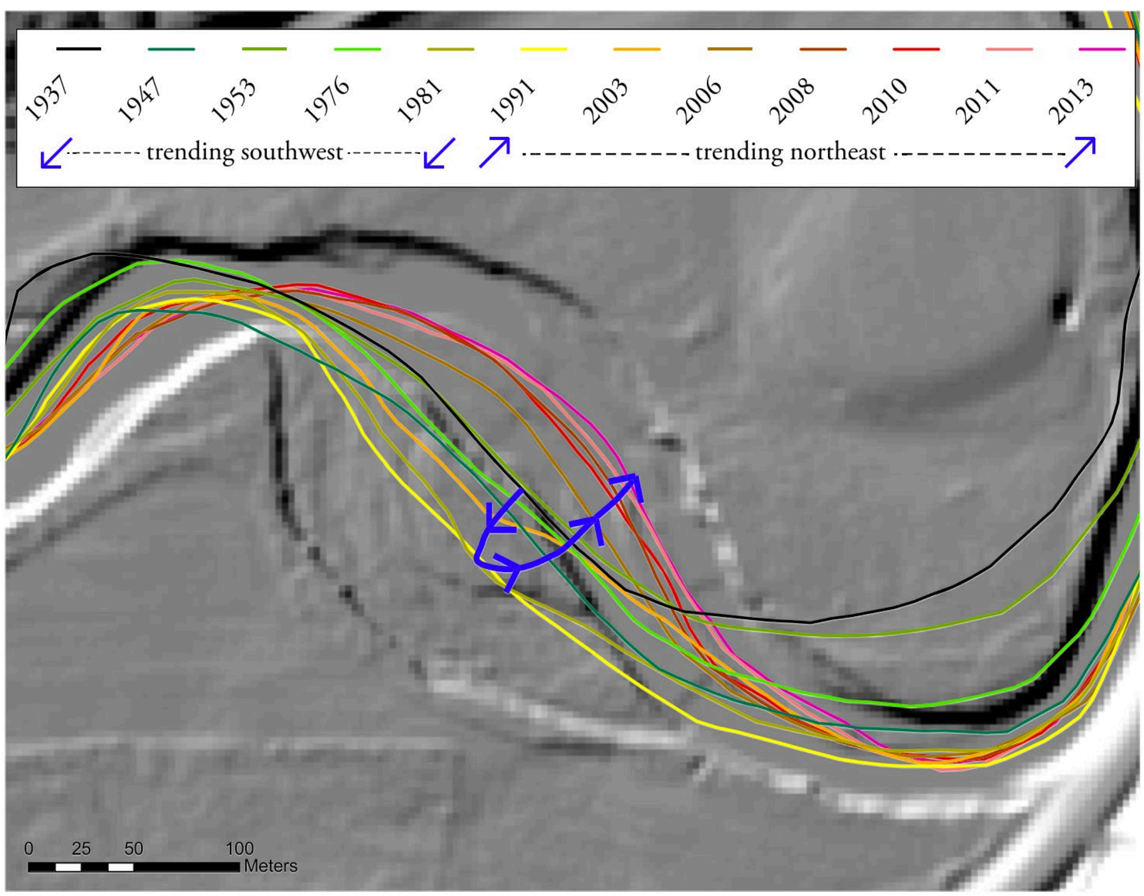


Figure 2-6. One example of a reversal for a reach of the Root River. The reach migrated approximately 40 m southwest from 1937 to 1991, followed by 85 m of northeasterly migration between 1991 and 2013. For this reach, the observed net migration is 45 m (0.6 m/yr) if no photographs existed between 1937 and 2013, whereas the actual migration is 125 m (1.6 m/yr). The LiDAR hillshade confirms southwestward migration followed by a reversal to its location in 2013 (dark-pink line).

How does timescale dependence vary with degrees of channel dormancy and reversals?

Numerical simulations using a statistical model allowed us to explore the role of channel dormancy and reversal frequency in migration measurements. When reversals were absent in modeled migration measurements, channel dormancy accounted for a very slight timescale dependence (~1% underestimate, Figure 2-7). The degree of timescale dependence/bias increased with reversal probability/frequency- illustrated by decaying cumulative migration rate ($\Delta x/\Delta t$) with increasing time interval ($\Delta t$). As reversals increase from 1% to 10%, migration distance and rate measured over 100 years are underestimated from 4% to 30% relative to a channel with no reversals (Fig. 2-7). The bias decreases with measurement interval until gross migration is completely unbiased by reversals at $\Delta t = 1$. This finding suggests that decay in empirical migration rates with increasing measurement timescale (Fig. 2-5) may reflect measurements incorporating more reversals and periods of dormancy. Rate convergence and asymptotic trends are also evident in the synthetic/modeled migration data (Appendix C, Figs. A4a & A4b).

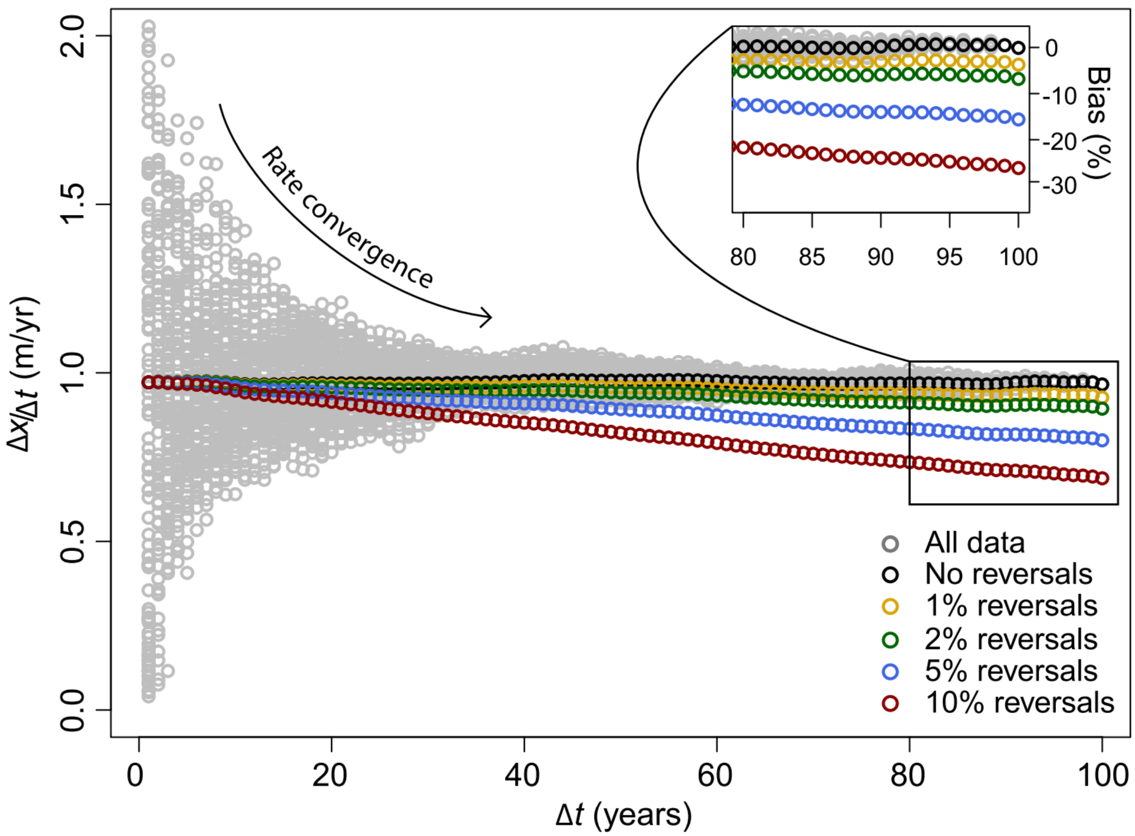


Figure 2-7. The model results demonstrate how high variability of short-term modeled migration rates ($\Delta x/\Delta t$, grey circles) converges towards a long-term average, a trend similar to that in empirical migration measurements (Figure 5). Black circles are mean rates over each measurement timescale (e.g., $\Delta t = 1, 2, 3, \ldots, 100$). Colored circles reflect the same, with the addition of reversals to the model simulations. Measurement bias increases rapidly as reversal frequency and measurement timescale increase, illustrated by incrementally lower values of modelled migration rates ($\Delta x/\Delta t$) relative to the scenario with no reversals.

How do actual changes in channel migration influence observed timescale dependence?

Additional simulations addressed whether actual temporal changes are distinguishable from timescale dependence, and whether the magnitude and direction of such changes make a difference. We sought to emulate a range of possible changes in migration rates, where each scenario involved a 1.25, 2, 5, or 10-fold change (increase and decrease) in migration rates half-way (50 years) through the 100-year simulations. All simulations included a 10% probability of reversals to maintain consistency. Increasing or decreasing modelled migration merely translated trends relative to the base case scenario of 10% reversals (Fig. 2-8). This finding matched the empirical trends of Zone 2, which are shifted/translated upward (Fig. 2-5, Zone 2, relative values of trend asymptotes) due to faster migration rates relative to Zones 1 and 3 (Fig. 2-9).

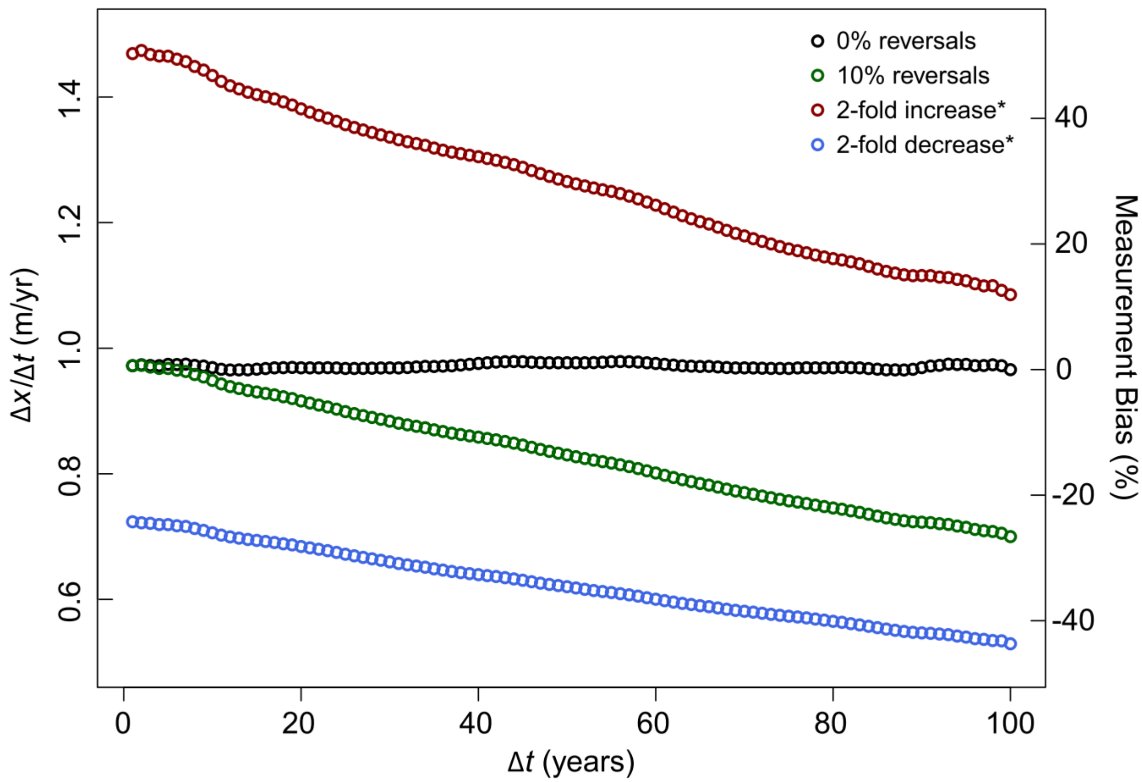


Figure 2-8. Comparing observed migration rates (Δx/Δt) over increasing measurement timescale (Δt) for different scenarios of temporal change. Black and green points reflect scenarios without and with reversals, but no temporal changes. Red and blue points both incorporated reversals, but also had a 2-fold decrease and increase in migration after year 50, respectively. These scenarios are translated (up or down) versions of the simple reversal scenario (green) with no changes. Thus, temporal changes in migration alone are not sufficient to emulate, nor exaggerate, timescale dependence without the effect of reversals, which would be indicated by a change in the trend slope.

Because the slope of modelled trends remained consistent regardless of rate changes, we can infer that, systematic changes in river channel migration are not sufficient to emulate, nor exaggerate, patterns associated with timescale dependence without the inclusion of channel reversals. Subsequent model simulations showed that combining a change in rates with biased sampling (i.e., predominance of contemporary short-term measurements relative to historical long-term measurements) can exacerbate or confound timescale bias. This is the result of artificially increased (or decreased) measurements for low- to mid-range time intervals (1-30 years), which effectively alters the slope of migration when plotted over $\Delta t$ (Appendix C, Figs. A4a & A4b). Thus, if contemporary and historical data respectively dominate short- and long-term measurements/records, inferences on temporal change in channel behavior are not conclusive without additional, independent evidence.

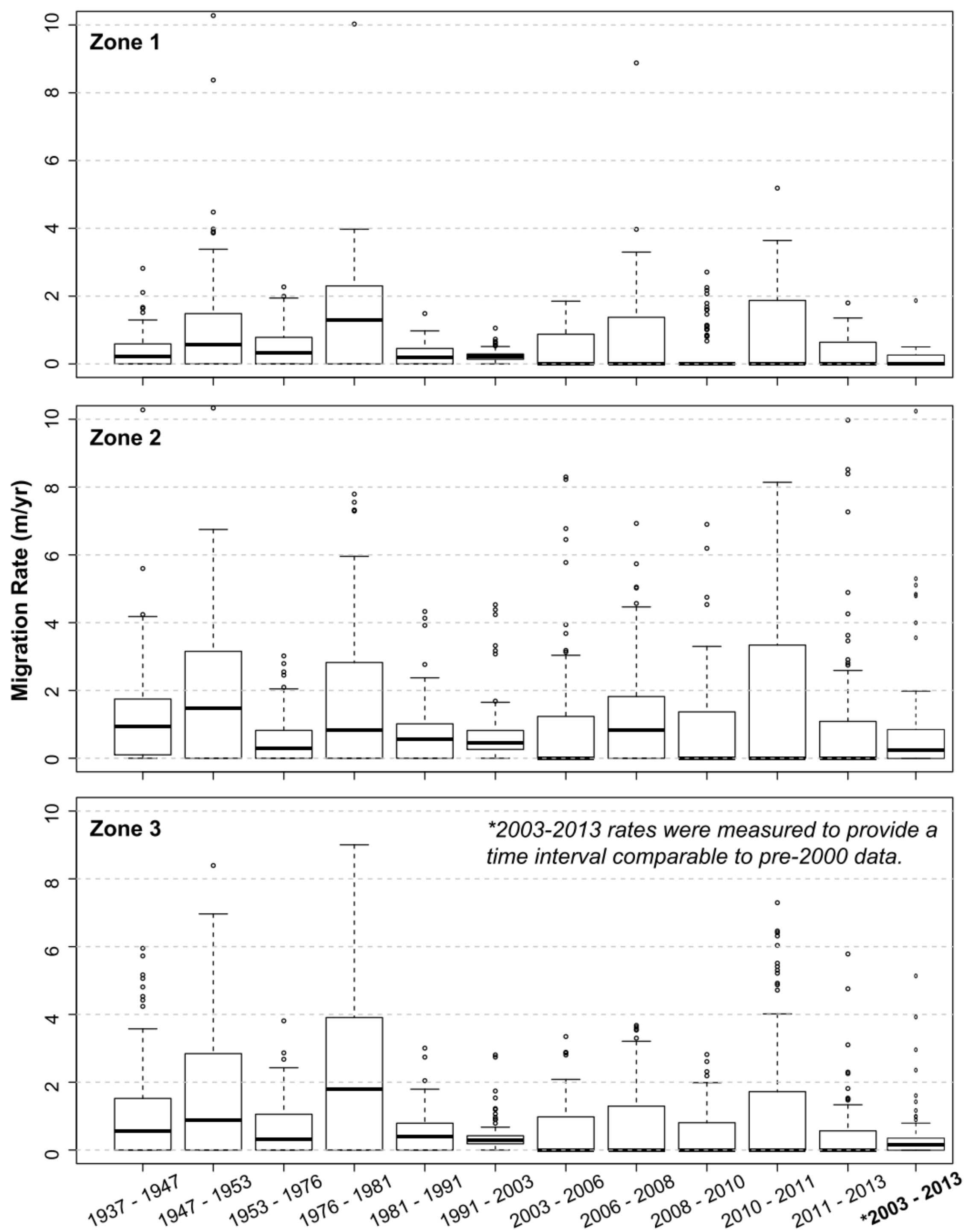


Figure 2-9. Boxplots of migration rates for each geomorphic zone of the Root River. The farthest right boxplot shows cumulative migration from 2003 to 2013, which provided a comparable measurement interval to those from before 1991 (see text).

## Predicting and adjusting measurements for timescale bias

Combined, the empirical and model results show us that timescale bias of migration measurements occurs, and this bias varies as a function of reversal frequency, measurement timescale, and changes in migration rate. While a lack of consistent short-timescale empirical measurements preclude the ability to eliminate timescale dependence, our model demonstrates that we can use estimates of reversal frequency to discern the percent of bias/underestimation in a given migration rate measurement for a given measurement interval. We tested the fit of four linear models to predicting bias using: reversal frequency, time interval, as well as the sum and products of the two using Akaike's Information Criterion (AICc, Burnham and Anderson, 2002). AICc measures the relative quality of multiple models using the trade-off between goodness-of-fit and model complexity. Models using reversal frequency or measurement timescale alone were both significant predictors ($p < 0.001$, $r^2 \sim 0.49$ & 0.35), but the fit was markedly improved by including both predictors in a multiple linear regression model (δAICc > 500). The final multivariate linear regression model (Eq. 3, $r^2 = 0.998$) enables one to adjust, or 'correct', for the bias with a known (or estimated) reversal frequency and measurement interval:

$$U = -0.035R \times 0.021\Delta t + 0; \quad (3)$$

where U is the percent bias/underestimate, R is the reversal frequency percent ($p < 0.001$) expressed as 0 to 100, and Δt is the measurement timescale ($p < 0.001$). While it is rare to have precise knowledge of reversal frequency, using evidence in aerial imagery or high-resolution topography to estimate a range of possibilities will improve estimates of gross sediment remobilization from channel migration by reducing bias inherent in long-term measurements.

To what degree, if any, have migration rates along the Root River changed over time?

We visually and statistically evaluated empirical migration data to determine whether the medians or distributions of migration rates exhibited any systematic changes over the period of study (Figs. 2-4a & b, Fig. 2-9). For 90 comparisons of migration rates measured before 1991 and those between 1991-2013, the medians and distributions increased significantly in 0% (0/90) and 14% (13/90) of comparisons, respectively ($p < 0.05$, Mann-Whitney-Wilcoxon and Kolmogorov-Smirnov tests). When relaxing our level of significance to 80% ($p < 0.2$), the medians and distributions still only exhibit significant increases in 1% and 39% of comparisons (Appendix B, Tables A1 and A2). However, these results are biased to favor the conclusion that migration rates have increased based on our previous empirical and model results (Figs. 2-5 & 2-7), which indicated that measurements over longer Δt values (i.e., measurements taken prior to 1991; Δt = 6–23) are likely biased low relative to those from 2003-2013 (Δt = 1-3). Despite the predisposed results, they only suggest a minor increase in Root River migration rates over the period for which flows have increased.

One approach for alleviating timescale bias is to aggregate multiple short Δt intervals for contemporary measurements to better match the longer Δt intervals of historical measurements preceding 1991 (Δt = 6–23). The MWW and K-S tests indicated no increase in the medians or distributions of migration rates (0/18), even when using a rather high $\alpha = 0.2$ (Fig. 2-8, Appendix C, Tables A1a and A1b, **bold** rows). This provided a second, unbiased, line of evidence that migration rates have not systematically changed despite significant changes in flow throughout the 76-year study period. Two implications thus arise: (1) the Root River is predominately not responding to increased flows with increased migration (Figs. 2-9, 2-4a & 2-4b), and (2) comparing disparate measurement timescales can introduce sufficient bias to alter results and sway inferences of channel adjustment, as corroborated by our model results (Fig. 2-8).

The previous pair of comparisons assessed the effect of comparing measurements with similar versus dissimilar measurement intervals. However, they did not address the commonly encountered situation in which historical measurements are inherently biased toward longer Δt values due to lower frequency of air photo acquisition. To examine the effects of this sampling bias and investigate a third line of evidence to determine whether migration rates have changed, we found seven reaches (3-29 km) with historical image pairs obtained at low-Δt intervals (Δt = 1-5, and 11 years) comparable to those from 2003-2013 measurements (n = 105 comparisons). Results from Mann-Whitney and Kolmogorov-Smirnov tests indicated that medians and distributions exhibited increased migration in only 14% and 18% of 90 comparisons with $\alpha = 0.05$ (Appendix B, Tables A2a & A2b). Furthermore, all but one of these significant increases occurred for comparisons with longer measurement intervals for the historical image pair (1962-1973). This finding is consistent with both empirical (Fig. 2-5) and model results (Fig. 2-7) that suggest longer measurement intervals will exhibit systematically lower values relative to shorter measurement intervals, potentially causing false positive results. Excluding one reach with considerably higher georeferencing uncertainty, these results were robust regardless of whether we retained or discarded measurements falling below the LoD.

Our results provided three lines of evidence that channel migration has not exhibited significant increases over the 76-year study period in response to increased flows. These results appear to contradict the physical explanation for an expected direct relation between flow and channel migration rates; increased flows tend to increase shear stresses along meanders, (Schook et al., 2017). However, sand and gravel-bed river channels adjust their geometry and slope to increase uniformity of sediment transport, and thus dampen responses to changing flow conditions (Church & Ferguson, 2015; Phillips & Jerolmack, 2016; Call et al., 2017) so adjustments may be driven more by sediment supply and transport capacity, rather than flow (Winterbottom, 2000). Our results also affirm that the timescale dependence for Root River channel migration measurements is not an artifact of differing rates for historical and contemporary data.

## Conclusions

Both empirical and modelled results demonstrate that migration rates are dependent upon the measurement interval. Short-term measurements (< 10 years) are dominated by high variability reflecting periodic bursts of migration. On the other hand, long-term measurements (> 25 years) converge asymptotically as measurements reach a 'characteristic timescale' where all variability has been sampled and subsequent measurements are relatively constant, barring significant long-term changes. In addition, long-term measurements of gross migration, and thus, sediment flux estimates, are underestimated as the result of channel reversals that erase portions of the erosional record. Thus, the timescale of channel migration measurements affects which question(s) they are suitable to address. Without a sufficient number of short-term

measurements, extrapolations will necessarily distort long-term sediment remobilization projections, sediment budgets, sediment flux estimates, and perceptions of fluvial change. Only sufficiently long intervals (> 20-25 years) beyond the 'characteristic timescale' are capable to answer whether a channel has undergone significant long-term changes (i.e., new equilibrium) when compared with similarly long-term measurements. Multiple short-term measurements are necessary to sample the episodic nature of channel migration, thereby providing a more comprehensive understanding of channels' short-term response to changes in flow and sediment flux. These results reinforce our conclusion that authors should use caution and similar measurement intervals when interpreting fluvial changes and causal mechanisms from aerial-based measurements of channel activity.

Empirical and modelled data both confirmed that migration rate measurements are increasingly underestimated as a function of channel reversal frequency, with insignificant effects from channel dormancy. Measurement bias favors the inference that contemporary channel migration rates have increased because of mismatched sampling intervals in contemporary and historical aerial photograph records. Furthermore, we conclude that long-term migration rates underestimate contributions from streambanks for sediment budgets or fluxes without accounting for or correcting bias using an observed or estimated frequency of reversals (Eq. 3). Before and after accounting for measurement bias in our data, we find no empirical evidence that the Root River has responded to increased flow with any significant increase or decrease in migration in subsequent decades. This reinforces the notion that without an understanding of sediment supply, no simple relationship exists between discharge and migration rates alone.

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